DISSERTATION ABSTRACT

NUMERICAL SIMULATION ON LOCAL-CONTACT MICROWAVE-HEATING INJECTOR (LMI) SYSTEM

(局所接触型マイクロ波加熱式噴射装置の数値シミュレーション)

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Abstract

Heating fuel is one of the most critical issue related to an improvement on fuel atomization and evaporation. The current study focus on the analysis of electromagnetic energy heating generated inside injector to heat the fuel flow and this system is called “Local-contact Microwave-heating Injector” (LMI). This scheme is expected to improve evaporation of fuel spray for enhancing combustion performance and reducing emissions of internal combustion engine.

A comprehensive studies of numerical and experimental was conducted to further analyzed heating phenomena and spray characteristics of LMI system. Spray characteristics of ethanol injected from LMI injector was experimentally investigated using High Speed Camera, CMOS camera and Laser Dispersion of Spray Analyzer (LDSA). It was found that local heating of fuel has the significant impact on droplet diameter and spray structure of ethanol fuel.

Simulation study was proposed to predict the occurrences related to microwave heating process that are difficult to evaluate in experimental study. Combination phenomena of electromagnetism, heat transfer and fluid dynamics were simulated using COMSOL Multiphysics. The time dependent of the equations applied on this system were solved using Backward Differentiation Formulation (BDF) solver. The results showed that temperature of ethanol was rapidly increased after imposing electromagnetic wave. Electromagnetic field intensity is sensitive to the geometry and shape of heating region and influences the temperature distribution. A little changed in the inner conductor diameter has significant effect on the behavior of electric field in the heating zone. Advance studies on this system is expected for further development and optimization of LMI system.

Keywords: Microwave heating, ethanol, electric field and heating zone.

1. Introduction.

A large number of internal combustion (IC) engines are recently utilized as power source for transportation and industrial applications. However, combustion of fossil fuel still generates several pollutant emissions that are extremely undesirable for the environment, therefore regulated. In the future, the passenger car will be markedly growing (IEA, 2011), consequently the fuel consumption become increased. On the other hand, the availability of fossil fuels are very limited, hence, the development on clean technology and efficient combustion of automotive industry is strongly required [1].

Recently ethanol fuel become attractive fuel as an alternative to gasoline. This fuel has high octane rating and high oxygen content which can possibly run engine with less knocking, high performances and low emissions [2]. Cleaner burning of this fuel leads the pressure to increase ethanol content in much higher proportions (E85 or E100). However, Ethanol fuel has lower energy density (LHV = 26.8MJ/kg) compared with gasoline (LHV = 44.6 MJ/kg) and higher viscosity as well as latent heat vaporization that can possibly generate problems when it is introducing into combustion chamber [3-4].

Temperature of the fuel should be increased to accelerated evaporation and mixing with oxygen inside combustion chamber. Evaporation of fuel is important in determining burning characteristics such as ignition delay, flame stability and completeness of burning. Several studies in [5-6] proposed technical solutions on improving evaporation fuel by heating evaporation chamber or directly heated fuel flow inside injector. They found the advantageous of heating fuel for enhancing fuel vaporization and mixing rate in combustion system.

The new feasible method for increasing temperature of fuel flow inside injector is using microwave heating. Microwave heating has several advantageous such as rapid, direct and uniform heating [7-8]. Current study uses microwave heating system to generate heat for fuel flow inside injector as in Figure 1. This system aim to add energy equivalent to the fuel flow inside injector and this system is called “Local-contact Microwave-heating Injector (LMI)” [9]. In LMI system, heating area was created inside head injector and connected with magnetron of microwave heating at 2.45GHz. This heating process can increase temperature of ethanol rapidly to around boiling point and improve spray characteristics [10].

This study aims to develop of LMI system performances through numerical simulation analysis. Several complex phenomena related to the heating generating system inside heating area are still unknown. This simulation also aim to improve performance through the appropriate design of heating zone of LMI system. Moreover, because of the physical difficulties in measure the temperature fuel distribution inside the area, then this simulation is

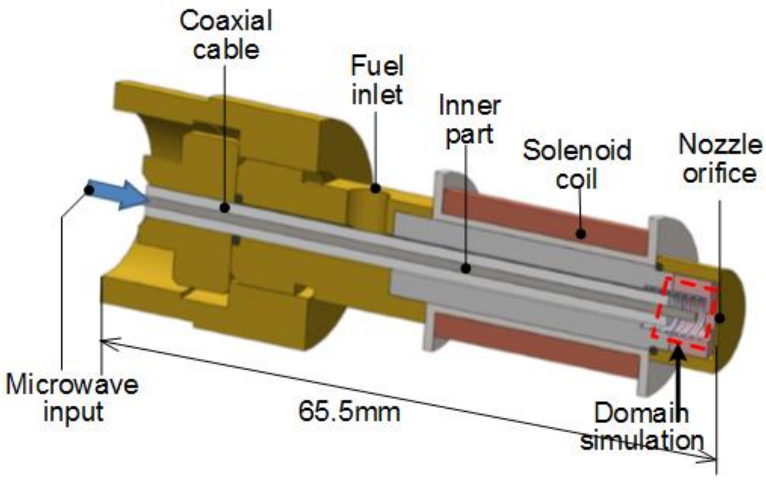


Figure 1. Schematic of LMI system.

expected to approach the problem by solution of partial differential equation of several physics interaction in the LMI system.

2. Numerical modeling on the heating zone of LMI system.

Numerical analysis was performed to investigate heating characteristics of ethanol flow inside heating zone of Local-contact Microwave-heating Injector (LMI) system. In this study, COMSOL Multiphysics was used to simulate two different schemes of heating generation system, microwave heating and convective heating. Microwave heating scheme solved transient equations of electromagnetic wave, heat transfer and fluid dynamics whereas convective scheme solved conjugate heat transfer between solid and fluid flow. Two models geometry of the inner part, square and round tip, were also developed and simulated in microwave heating scheme. Each model was also varied at different inner diameter to evaluate the effect of geometry and shape of heating zone on the temperature field distribution inside heating area.

Electromagnetic field applied to the system is calculated based on the Maxwell's equation and the following equation is suggested [11].

$$\nabla \times \frac{1}{\mu_r}(\nabla \times E) - k_0^2 (\varepsilon_r - \frac{j\sigma}{\omega \varepsilon_0}^{"})E = 0 \tag{1}$$

Where E is the electric field, ε_0 is electric permittivity of free space. ε_r is the relative permittivity, μ_r is the dielectric relative permeability, σ is the electric conductivity, ω is the angular frequency and k_o is the wave factor number of the free space.

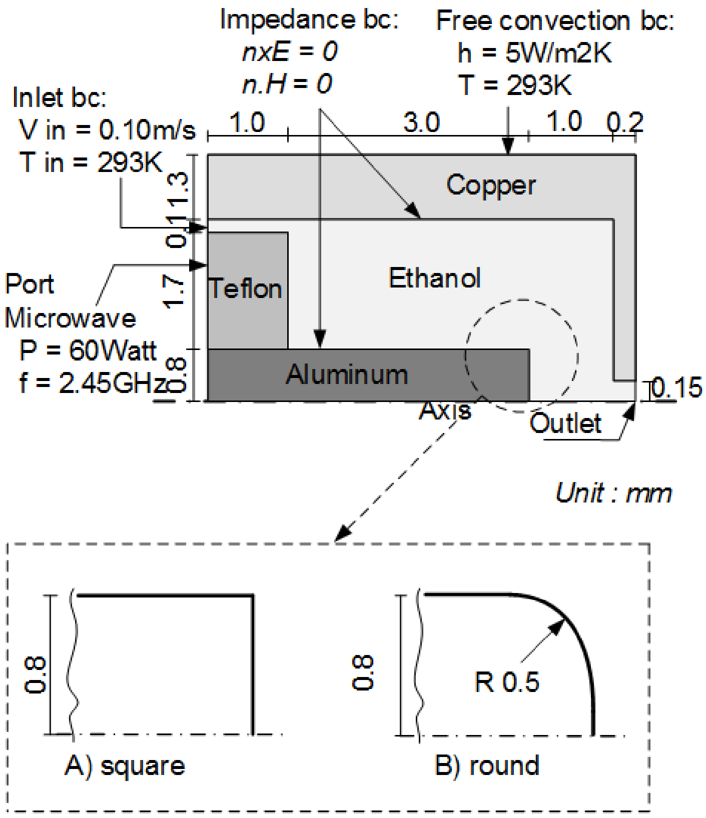


Figure 2. Schematic geometry and two model simulated

The transient temperature behavior in the heated material is obtained by solving the following energy equation of the system. Heat generation due to absorption of microwave energy inside the system can be expressed as [12].

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p u \cdot \nabla T = \nabla \cdot (k \nabla T) + Q \tag{2}$$

Where the first and the second left side equation represents the internal energy heat and kinetic energy of the system, respectively, while in the right side shows the conduction heat and energy heat generation. Volumetric energy heat generated (Q) by microwave heating can be calculated from the following equation:

$$Q = \omega \varepsilon_0 \varepsilon'' |E|^2 \tag{3}$$

Conservation equations of mass, momentum and energy equation of fluid flow were solved with time dependent state in the form:

- Conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \tag{4}$$

- Momentum equation:

$$\rho\frac{\partial u}{\partial t}+\rho(u\cdot\nabla)u=\nabla\cdot\left[-pI+\mu(\nabla u+(\nabla u)^{T})-\frac{2}{3}\mu(\nabla\cdot u)I\right]+F \qquad (5)$$

Ethanol fuel is modelled as having dielectric properties of electrical conductivity 1.35e09 S/m, relative permeability 1.67, and relative permittivity (real part 24.3 and imaginary part 22.866). Teflon, a dielectric material, is used as the electromagnetic wave guide that has properties of electric conductivity of 1.0e-32S/m, dielectric permittivity of 2.1 and relative permeability of 1.0.

Boundary condition consist of port boundary of microwave heating with dissipated power of 60Watt and frequency of 2.45GHz. Walls of the heating zone consist of metallic materials (copper and aluminum), that will be reflected electric and magnetic field from the surface of the material [12].

$$n\times E=0 \text{ and } n\cdot H=0 \qquad (6)$$

3D Geometry of domain simulation was discretized into finer element mesh of tetrahedral mesh. A number of 133,799 element meshes was generated from domain simulation and solved in time dependent by Direct solver scheme. Properties of simulation can be seen in table 1.

Table 1. Properties of simulation study.

Description	Value
Fuel	Ethanol
Fuel temperature	293.15K
Fuel pressure	0.3MPa
Velocity inlet	0.1m/s
Microwave power	60W
Frequency	2.45GHz

3. Experimental measurement analysis.

Spray characteristics of fuel injected from LMI were measured and analyzed in this paper to evaluate the effect of electromagnetic heating radiation on the ethanol spray. Direct measurement on spray behavior was conducted using High Speed Camera, CMOS camera and Laser Dispersion of Spray Analyzer (LDSA). Temperature of tip injector was also measured using K-type thermocouple. This study also consider the imaging spray analysis of fuel injected from LMI injector between heating and non-heating. Spray photos of the spray fuel were subtracted and analyzed to evaluate the spray characteristics of LMI system.

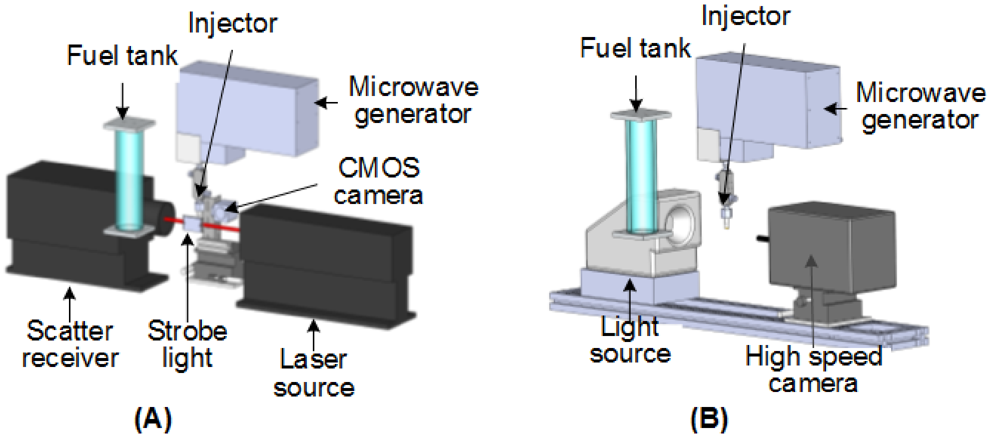


Figure 3. Schematic of experimental apparatus for spray analysis, (A) LDSA and CMOS camera, (B) High speed camera.

4. Result and analysis.

Simulation study is performed to simulate the physics phenomena of microwave heating process in LMI system. Spatial distribution of dielectric field as well as power dissipated in the heating area can be seen in Figure.4. The figure shows the maximum electric field distribution around the tip of inner part for both models and consequently the temperature distribution become increasing. This characteristics were evaluated during imposing 60Watt power into the system. Electric field can be reached 9.54e4 and 7.72e4V/m for round and square model respectively. Power dissipated into ethanol can be reached 14e0W/m3 and 9.30e9 for round and square model respectively.

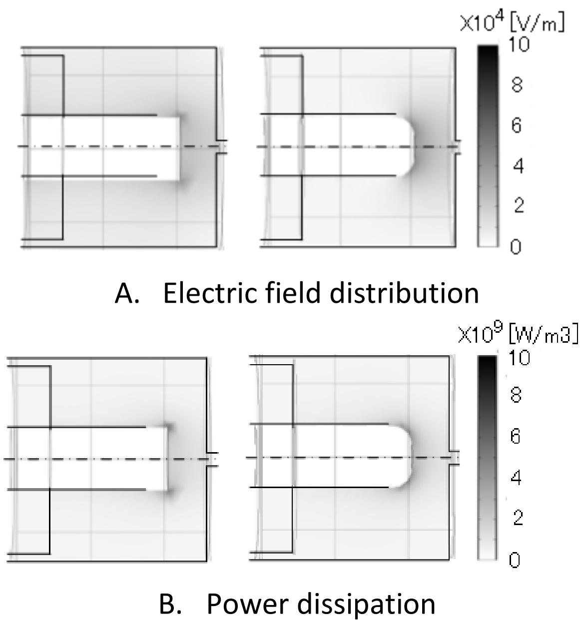
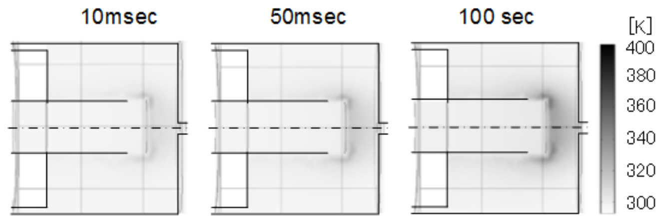


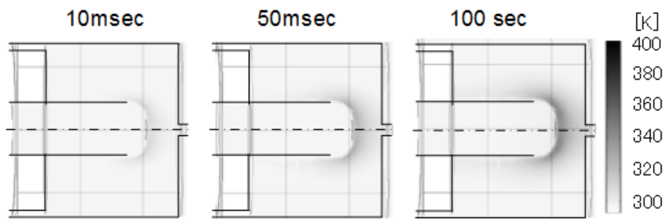
Figure 4. Electric and dissipation distribution of two differences model simulated during imposing power (50msec).

Rapid heating of ethanol is clearly shown in the short time after imposing electromagnetic power into the system. Microwave heating can generate heat inside the material based on the mechanical vibration on dipolar molecule of water inside the fuel. Interaction between electromagnetic wave radiation and dielectric properties at high frequency generates heat inside ethanol. Temperature field distribution inside heating zone of ethanol fuel can be seen in Figure 5. In square model the maximum temperature generates in the edge of inner part while in the round model it moves along the round tip. It is proportional with the electric field distribution and power dissipated inside heating area in Figure 4. In 100msec of heating time the temperature can reach around 400K for the square model and 393K for the round model, however, the distribution was not uniform and maximum can be reached at the tip of inner conductor where the power dissipated was optimum.

In the tip of injector the temperature of fuel was evaluated and compared with the result of experimental measurement. Both simulation and experiment are in fairly good agreement of temperature at the tip injector during injection time. Small difference is several point can be due to the properties of simulation and geometry that simplified from the complex geometry of real LMI injector.



A. Square model



B. Round Model

Figure 5. Temperature field distribution of two model simulated

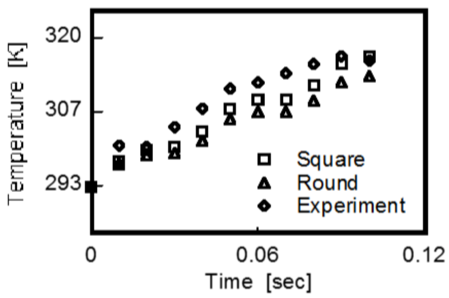
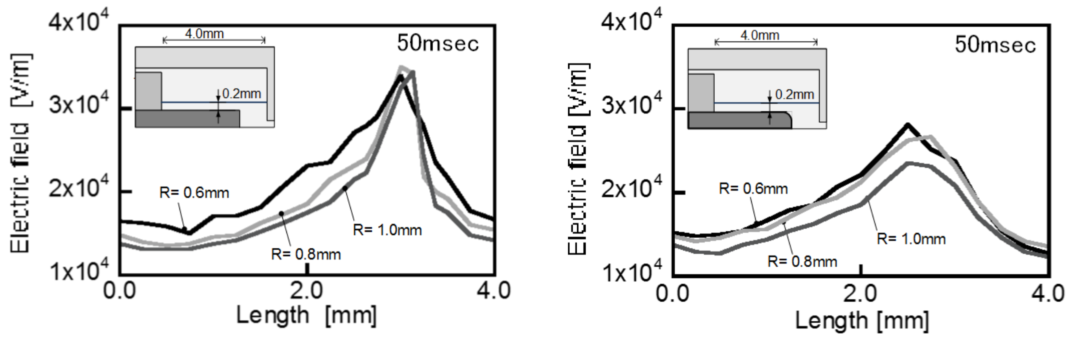
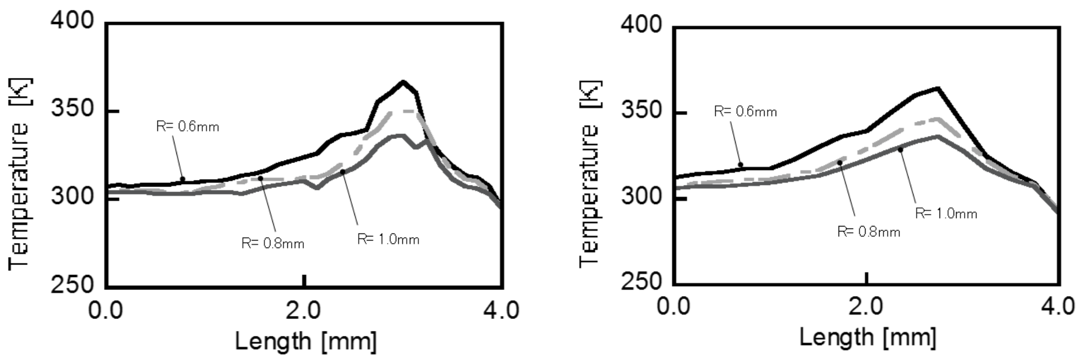


Figure 6. Temperature history at tip injector.

In this simulation we evaluated also the effect of inner diameter of conductor for the two model. Electric field distribution was evaluated along heating area (4.0mm) and 0.2mm from the surface of inner conductor. The bigger the diameter the lower the electric field strength generated inside the heating zone, and leads the temperature become lower inside the zone. In the bigger distance between the conductors the amplitude of electromagnetic wave become bigger and hence the temperature increases. For the square model the maximum Temperature field is 367K, 350K and 339K for the inner conductor radius of 0.6mm, 0.8mm and 1.0mm respectively. Whereas in the round model the maximum temperature field is 365K, 347K and 337K for the inner conductor radius of 0.6mm, 0.8mm and 1.0mm respectively.



A. Electric field distribution



A. Temperature distribution

Figure 7. Electric field and Temperature distribution of the two mode simulated (50msec).

Spray images of the fuel spray from LMI system were also analyzed in this study to evaluate the effect of heating fuel on the droplet size of the spray fuel. Velocity distribution of the droplets was also examined. In each spray, velocity of 100 droplets was measured and analyzed in post processing software. Figure 8 shows the droplet size characteristic between heating and non-heating spray. In the next histogram of velocity distribution, it is clearly that heating droplets move a little faster than non-heating droplets. This characteristic can promote better evaporation due to an increasing in velocity. In additional, heating fuel also can improve the viscosity and surface tension of the fuel and promotes the complete combustion of the fuel.

Spray characteristics of fuel injected from LMI such as sauter mean diameter (SMD), droplet distribution and spray structure were analyzed simultaneously. Direct measurement on spray behavior was conducted using High Speed Camera, CMOS camera and Laser Dispersion of Spray Analyzer (LDSA). It was found that local heating of fuel has the significant impact on droplet diameter of ethanol fuel (Figure 8). Droplets size of the spray become smaller when the fuel experienced microwave heating [10]. It can also be seen that distribution of droplets

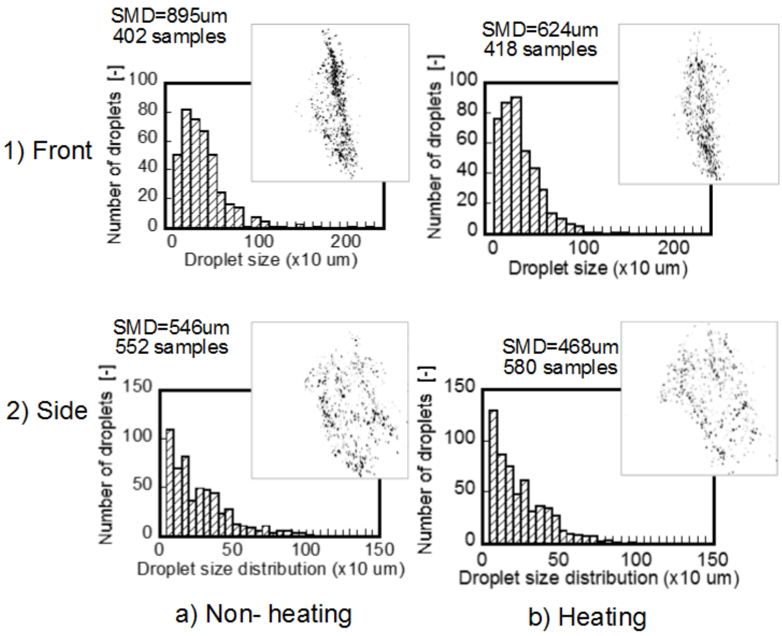


Figure 8 Droplet size analysis between heating and non-heating spray

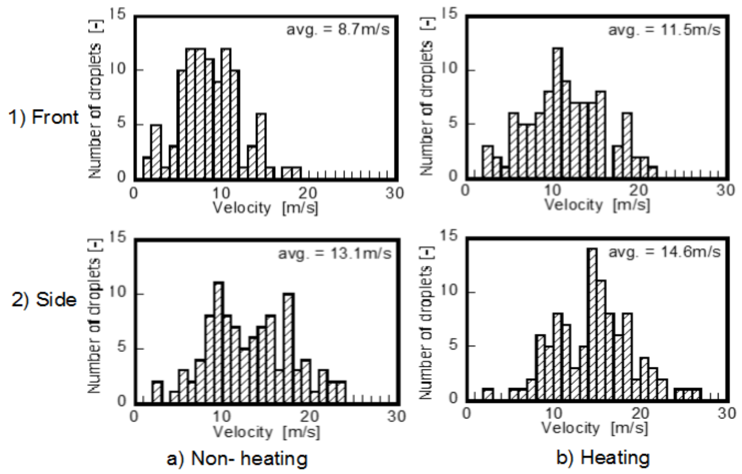


Figure 9. Velocity characteristics of heating and non-heating spray

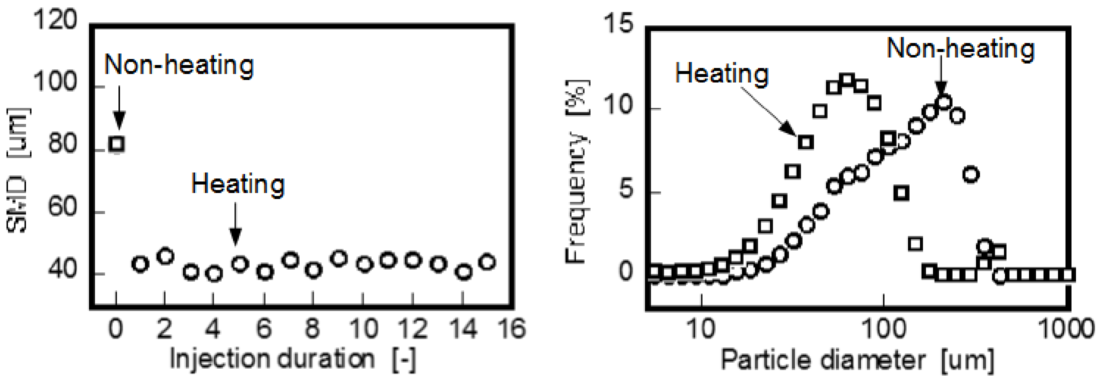


Figure 10. Spray characteristics of LMI; A is droplet size and B is particles distribution

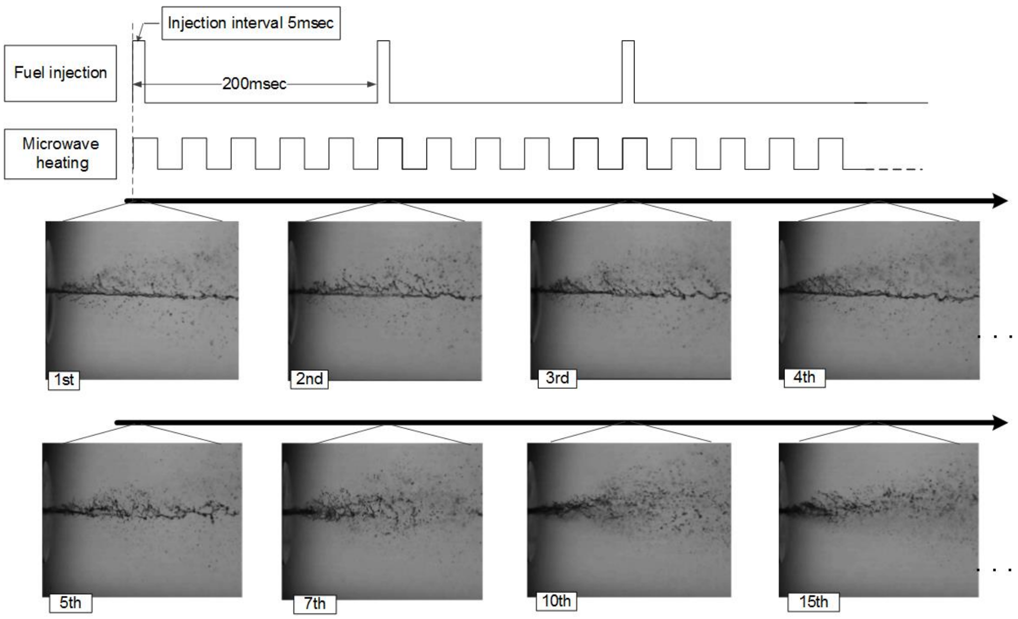


Figure 11. Spray components of several injection time.

become smaller in the heating spray. In figure 11, the spray structure was changed during several injection time. The liquid spray become shorter by the increasing of injection time where the temperature of fuel increases. The spray characteristic of ethanol become improve during microwave heating radiation inside LMI system.

5. Conclusion

Numerical simulation was performed to analyze the unknown phenomena inside heating area of LMI system and validated with the measurement data. The results showed that electromagnetic heating had significant impacts on temperature distribution of the fuel. Temperature of ethanol was rapidly increased into around boiling temperature after applying microwave heating. Geometry and shape of heating area are sensitive to the temperature field distribution. This results can be useful for further development and optimization of LMI system.

This heating system also improves the spray characteristics of ethanol. Droplet diameter in terms of SMD can be reduced around 50% during heating. Moreover, heating system increases the droplet velocity during injection and become one of the advantageous of the LMI system on improving spray performances.

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平成 27 年　1 月　27 日

学位論文審査報告書（甲）

1．学位論文題目（外国語の場合は和訳を付けること。）

Numerical simulation on local-contact microwave-heating injector (LMI) system

（局所接触型マイクロ波加熱式噴射装置の数値シミュレーション）

2．論文提出者　(1) 所　　属　システム創成科学専攻

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3．審査結果の要旨（600～650 字）

当該学位論文に関し，平成 27 年 1 月 27 日午前に第 1 回学位論文審査会を開催，提出された学位論文および関連資料に関する検討を加え，同日午前の口頭発表後，第 2 回論文審査委員会を開催，協議の結果，以下の通り判定した．

液体燃料を用いる内燃機関では，機関温度が低い状態(冷間始動状態)での燃焼特性改善および排気特性改善が重要な課題の一つであった．冷間始動状態で液体燃料の蒸発を促進するために熱量供給する必要があるが，マイクロ波を利用した輻射による加熱法を提案，新たな燃料噴射装置を設計，製作し，その機能を検証した．新たに取り組んだ数値シミュレーションの結果と，画像解析の結果から，エタノール混合燃料の微粒化が促進されること，マイクロ波による熱量輸送の仕組みが可視化できること，がわかった．

以上より本論文は，内燃機関冷間始動特性改善に有効な加熱機構に関する知見を得ており，工学的な寄与が大きく，博士(工学)の学位に値するものと判定した．

4．審査結果　(1) 判　　定（いずれかに○印）　合　格　・　不合格

(2) 授与学位　博　士（工学）